

JAROSŁAW SZLUGAJ<sup>1</sup>, BARBARA RADWANEK-BAK<sup>2</sup>

## Lithium sources and their current use

### Introduction

Lithium is the lightest metal in the periodic table with a specific density of only 0.534 g/cm<sup>3</sup>. It is one of the alkali metals. It is very soft (Mohs hardness 0.6) with a silvery-white color, which, however, quickly turns darker (up to black) as a result of oxidation. Its melting point is 181°C and boiling point is 1,342°C. Due to its high reactivity, it does not occur in nature in its metallic form, but in chemical compounds of ionic structure (e.g. salts, oxides, hydroxides). For this reason, and because of its flammability and potential explosiveness, it must be stored in mineral oils, under vacuum or in noble gases. It has the highest heat capacity of all the solid elements and is an excellent conductor of heat and electricity. Its name comes from the Greek word *lithos*, meaning stone (Bolewski et al. 1976). It was discovered in 1817 by the Swedish mineralogist, Johan Arfvedson, as a component of petalite, who also identified it a little later in spodumene and lepidolite. Lithium metal was obtained as late as 1821,

✉ Corresponding Author: Jarosław Szlugaj; e-mail: szlugaj@min-pan.krakow.pl

<sup>1</sup> Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Kraków, Poland; ORCID iD: 0000-0002-4537-209X; e-mail: szlugaj@min-pan.krakow.pl

<sup>2</sup> Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Kraków, Poland; ORCID iD: 0000-0002-1280-9902; e-mail: brad@min-pan.krakow.pl



and as late as 1855, larger quantities were produced by electrolysis of lithium chloride by Robert Bunsen and Augustus Matthiessen. In total, more than 100 different lithium-containing minerals are known, but only a few are currently economically significant (spodumene, lepidolite, petalite, hectorite, zinnwaldite, amblygonite, jadarite, and a few others) (Bradley et al. 2017; Kavanagh et al. 2018). Its estimated average content in the Earth's crust is about 17–20 ppm, in magmatic rocks it is of the order of 28–30 ppm, and in sedimentary rocks its concentrations can reach 53–60 ppm (Evans 2014; Kunasz 2006).

The development of technology in recent decades and years has made this metal one of the most desirable on the market due to its wide spectrum of not only traditional but also new applications, especially in energy and nuclear weapons, and in the automotive and electronics industries. In 2018, lithium was added to the list of elements critical to US national security and economy (there are now thirty-five) (USGS 2021). In 2020, lithium was also added to the list of critical raw materials for the EU economy (there are currently thirty) (Eurostat 2021).

Due to the increasing use of lithium raw materials in the world, the purpose of this paper is to analyze the management of its raw materials. It particularly focuses on the increased development of this market in the second decade of the twenty-first century (as of August 2021).

## 1. Lithium minerals and their deposits

Although lithium is commonly present in nature in trace amounts, there are only three sources of lithium of significant economic importance. These are: pegmatites, continental evaporites – saline lakes (salt flats) and lithium-bearing clays (Table 1).

Pegmatite lithium deposits are most commonly associated with LCT (lithium-cesium-tantalum) granitoid pegmatites. They usually have a typical zoned structure they contain

Table 1. Types of lithium mineral deposits in the world

Tabela 1. Typy złóż kopaliny litu na świecie

| Deposit type                         | Average lithium content    | Share in the world resources* |
|--------------------------------------|----------------------------|-------------------------------|
| Pegmatites                           | 1.5–4.0% Li <sub>2</sub> O | 26%                           |
| Continental brines                   | 0.04–0.15% Li              | 58%                           |
| Geothermal brines                    | 0.01–0.035% Li             | 3%                            |
| Oilfield brines                      | 0.01–0.05% Li              | 3%                            |
| Lithium bearing clays with hectorite | 0.4% Li <sub>2</sub> O     | 7%                            |
| Zeolites                             | 1.8 Li <sub>2</sub> O      | 3%                            |

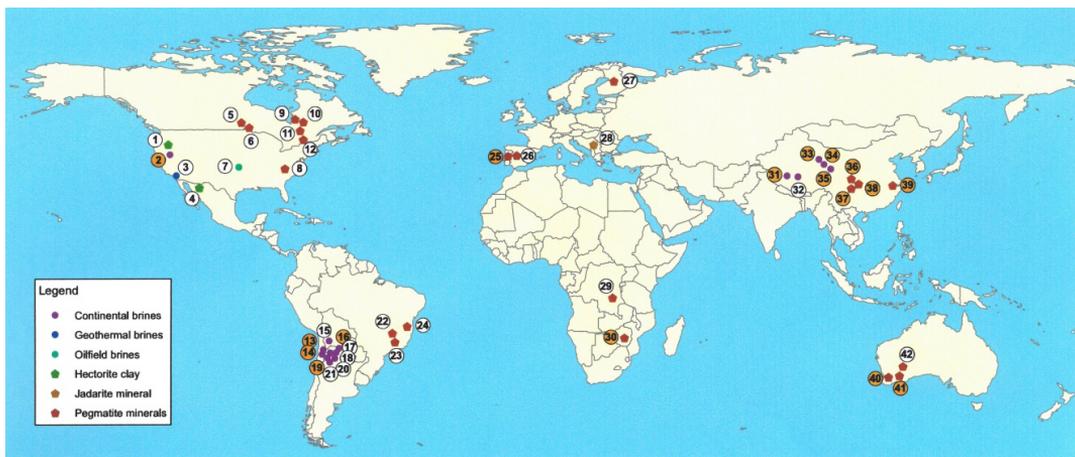
\* By (Cronwright 2019) – all types of brine resources constitute 78% of the total resources, a further 19% from pegmatite deposits and ca. 3% from lithium-bearing clay minerals and zeolites.

Source: own study based on Evans 2014 and Bradley et al. 2017.

lithium aluminosilicates: spodumene, petalite, lithium micas (e.g. lepidolite, zinnwaldite, effesite), and lithium phosphate amblygonite. They occur near granitoid intrusions, mainly in Precambrian rocks, on all continents. Coarse crystalline mica granites with lepidolite are of subordinate importance.

Continental brine deposits occur in arid, often high mountain climates, with evaporation over precipitation, in areas of tectonically controlled subsidence. They are associated with magmatic rocks that may be the primary source of lithium and zones of geothermal activity. Salt flats usually occupy large areas. They are divided into so-called mature basins, in which salts of high purity and significant salt concentration occur, and less rich salt muds, where salts are accompanied by clastic components; these occur mainly in South America (Chile, Argentina, Bolivia), North America and China. Lithium occurs as carbonate or chloride co-occurring with many other salts: Na, Br, K, and B. These deposits are classified as evaporite due to the leading contribution of this process to the formation of the lithium concentration of the deposit. It is believed that a large part of continental lithium-bearing brines are supplied with this element from deep thermal waters. In recent years, so-called unconventional brines have also been identified, which have not been used yet due to lack of appropriate technologies. These include deep geothermal brines, as well as brines associated with oil and gas deposits.

Lithium-bearing clay deposits are associated with volcanic zones. They are usually formed lenses in dry climate conditions. The main mineral, lithium-bearing hectorite (a variety of magnesium-lithium smectite that is formed during hydrothermal alteration of



## Key to Numbers

- |                               |                         |  |                                     |                               |                              |
|-------------------------------|-------------------------|--|-------------------------------------|-------------------------------|------------------------------|
| (1) Kings Valley, USA         | (8) Kings Mountain, USA | (15) Salar de Uyuni, Bolivia           | (22) Mibra, Brazil                  | (29) Manono, D.Rep. of Congo  | (36) Sichuan Aba, China      |
| (2) Silver Peak, USA          | (9) James Bay, Canada   | (16) Salar de Olaroz, Argentina        | (23) Volta Grande, Brazil           | (30) Bikita, Zimbabwe         | (37) Jilajika, China         |
| (3) Salton Sea, USA           | (10) Rose, Canada       | (17) Salar de Cauchari, Argentina      | (24) Jequitinhonha, Brazil          | (31) Zhabuye Salt Lake, China | (38) Maerkang, China         |
| (4) Sonora, Mexico            | (11) Whabouchi, Canada  | (18) Salar de Rincon, Argentina        | (25) Guarda, Portugal               | (32) Dangdongcuo, China       | (39) Ningdu, China           |
| (5) Tanco, Canada             | (12) Val d'Or, Canada   | (19) Salar de Hombre Muerto, Argentina | (26) La Fregeneda, Spain            | (33) West Taiji Nat'ar, China | (40) Greenbushes, Australia  |
| (6) Separation Rapids, Canada | (13) Salar de Atacama   | (20) Sal de Los Angeles, Argentina     | (27) Lantta (and 3 others), Finland | (34) East Taiji Nat'ar, China | (41) Mount Cattin, Australia |
| (7) Magnolia, USA             | (14) Salar de Atacama   | (21) Sal de Vida, Argentina            | (28) Jadara, Serbia                 | (35) Qinghai Salt Lake, China | (42) Mount Marion, Australia |

Fig. 1. Distribution of major lithium mineral deposits in the world

Source: Brown et al. 2016

Rys. 1. Rozmieszczenie ważniejszych złóż kopalin litu na świecie

volcanic ash or glass or direct precipitation from saline solutions) co-occurs with another smectites. It can contain up to 600 ppm Li in its structure.

Lithic zeolite (jadarite) accumulations are of unique importance. Only one deposit is known so far Jadar in Serbia. Greisen deposits, in which lithium accompanies tin and tungsten ores and is sometimes recovered incidentally, are of secondary importance. The distribution of major lithium mineral deposits in the world is shown in Figure 1.

### 1.1. Pegmatite deposits

The largest currently recognized deposits are located in Australia, Canada, the USA, the Democratic Republic of Congo and Zimbabwe (Figure 1). Numerous smaller lithium-bearing pegmatites occur in China, Russia, Brazil, India as well as in Mali and Namibia (Next et al. 2019). A large but still poorly explored potential is hidden in deposits of Afghanistan, e.g. Nilaw in Laghman province, Parun in Badakhshan province) (Natkaniec-Nowak and Słowakiewicz 2010; Kavanagh et al. 2018).

Among European countries, lepidolite pegmatites have been known and used for a long time in Portugal (Barroso-Alvao, Guarda-Goncalo), in Spain (Fregenda-Almerenda area), in the Czech Republic (Cinovec) and France. New analyses and explorations are currently underway to verify the lithium resource as well as the co-occurring tantalum (Krzak et al. 2021). In recent years, thanks to intensive exploration, new pegmatite deposits have been discovered in Austria (Wolfsberg), Finland and Germany.

In Australia, deposits of lithium-bearing pegmatites occur predominantly in Precambrian formations of the Western Australian Shield, and more specifically, in granitoid intrusions intersecting metamorphic rocks of the Yilgran Block (Archaic). They are partially covered by Tertiary sediments and laterites. The largest deposit currently in production is Greenbushes. Its dimensions reach about 5 km long and 300 m wide. The spodumene content in the total mass of pegmatite is about 26%, while in the richest spodumene zone it can even exceed 50%. Measured resources for this deposit in 2012 were estimated at 0.6 million tonnes of lithium ore with an average  $\text{Li}_2\text{O}$  content of 3.2% (abbreviated: 0.6 million t/average content of 3.2%  $\text{Li}_2\text{O}$ ), indicated resources of nearly 118 million tonnes of ore/average content of 2.4%  $\text{Li}_2\text{O}$ , and inferred resources of 2.1 million tonnes/average content of 2.0%  $\text{Li}_2\text{O}$ ) (Brown et al. 2016).

Another large deposit is Mt Cattlin. It is formed by a series of pegmatite dikes located subhorizontally at depths of about 30 m among volcanogenic and intrusive rocks. Spodumene, zinnwaldite and lepidolite are present, accompanied by beryllium. Measured resources are estimated at 2.5 million tonnes of lithium ore (1.2%  $\text{Li}_2\text{O}$ ), indicated resources are at around 9.5 million tonnes of ore (1.06%  $\text{Li}_2\text{O}$ ) (Brown et al. 2016). Its operation began after a long break in 2016.

There is another large lithium mineral deposit nearby Mt Marion. It is built up by albite-spodumene pegmatites, with small amounts of rare metals. It has been exploited

since 1968 and its resources are estimated at 2.7 million tonnes of ore containing about 1.75%  $\text{Li}_2\text{O}$  (Brown et al. 2016). Flotation concentrates contain 6%  $\text{Li}_2\text{O}$ .

One of the latest lithium mineral mining projects is the Wodgina cassiterite deposit located in the Pilbara region of northwestern Australia. It lies within the greenstone belt of the Wodgina Greenstone. They are formed in a series of subhorizontal and almost parallel pegmatite dikes accompanying small granitoid intrusions. Spodumene is an accompanying mineral of cassiterite. According to 2017 estimates, the inferred lithium ore resources in this deposit are close to 198 million tonnes, with approximately 1.18%  $\text{Li}_2\text{O}$  content (Jaskula 2020). The deposit is mined using the opencast method.

Lithium mineral deposits in the USA have been recognized in the states of North Carolina and Dakota. The most important deposits include the pegmatite zone of the Kings Mt district in North Carolina, associated with the Appalachian orogen, and more specifically with granitoid intrusions intersecting the Lower Palaeozoic gneisses and crystalline schists. The useful mineral is spodumene, and less commonly amblygonite. Elevated concentrations of beryllium, tin, titanium zirconium and rare earth elements were also found in the pegmatites. The largest and first developed deposit here is Kings Mt, with reserves of over 20 million tonnes of ore with 10–20% spodumene. They were recognized as early as the beginning of the twentieth century but were mined occasionally. The dynamic development of mining was recorded in the 1950s and 1960s, when the region was one of the world's leading suppliers of lithium ores. The mine was closed in 1998 due to excessive costs compared to the South American lithium-bearing brine deposits just made available at that time. The lithium ore resource left in this deposit area is estimated at 2.5 million tonnes (Evans 2014).

South Dakota deposits are also associated with intrusions of Precambrian granitoids intersecting a series of metamorphic rocks: gneisses, quartzites, and crystalline schists. Among the pegmatites, the microcline-albite type dominates, with spodumene as the main lithic carrier, accompanied by amblygonite and lepidolite. Currently they are not in operation. Of subordinate importance are small pegmatite deposits of New Mexico, California, and other western states (e.g., Magnolia, Kings Valley, Salton Sea).

In Canada, lithium-bearing pegmatite deposits of the Canadian Shield occur in several provinces: Manitoba, Ontario, Quebec and in the Northwest Territories. The largest are located in the Bernic Lake area (Manitoba), where Archaic formations composed of metamorphosed sedimentary and effusive rocks are intersected by an intrusion of sodic granitoids associated with a variety of lithium-bearing pegmatites. The Tanco deposit is currently the most important. Its dimensions are: length 1520 m, width 1060 m. It was explored to a depth of 100 m. Lithium ore mining was stopped here in 2010. Reopening of the mine planned in recent years, is oriented towards the recovery of caesium, whose carrier is pollucite (Brown et al. 2016).

Other similar deposits of this region include: Bernic Cat Lake, operated in the 1970s–80s, Nama and Snow Lake. In addition to the lithium and caesium minerals, they also contain elevated content of beryllium and tantalum. In the province of Ontario, deposits of lithium-bearing pegmatites (Nakima, La Crua, Georgina, Nipigon) occur among gneisses dating

back to the archaic. Other large deposits are located in the province of Quebec: La Corne with resources of 18 million tonnes ore/1.26%  $\text{Li}_2\text{O}$  and Val d'Or et al. (Kavanagh et al. 2017). Significant prospects are associated with Precambrian albite or albite-spodumene granitoids of the Northwest Territory province. The prospective resources of this region are estimated at over 100 million tonnes of spodumene ores with 1–4%  $\text{Li}_2\text{O}$  content.

The African continent has a large, but still not fully recognized and utilized raw material potential. It hosts one of the world's largest pegmatite lithium mineral deposits of the LCT type Manono-Kitotolo in the Democratic Republic of Congo. Although its lithium resources are estimated at about 2 million tonnes, it was exploited only as a source of tin (cassiterite) and tantalum (columbite) in the past (1919–1982). This deposit occurs among metamorphosed Precambrian shales (mainly micaceous) intersected by granitoid intrusions. It is formed by several albite pegmatites occupying an area of about 15 km long and 800 m wide (Dewaele et al. 2015), the largest of which are: Roche Dure, Carriere de l'Este, Mpete, Tempete. In the near-surface lithium-enriched zone, ore with 10–25% spodumene content was found. The largest Roche Dure pegmatite has a proven length of 2.1 km and a thickness of 200 m. As per data of 2020, the total resource of the Manono-Kitotolo area is approximately 93 million tonnes of ore with 1.58%  $\text{Li}_2\text{O}$  and 998g/t Sn (Avsminerals 2021).

Another long-known deposit is Bikita, located in Zimbabwe. Like most pegmatite deposits, it occurs among Precambrian greenschist shales and quartzites of the Rhodesian-Transvaal shield and intruding granitoid rocks. The deposit zone made up of several pegmatite bodies here has dimensions of about 3 km long and 100–180 m wide. Among lithium minerals petalite and lepidolite dominate. The deposit is a 1,700-meter long and 270-meter thick dike of microcline-albite pegmatite of the LCT type. It has been exploited opencast since 1952, initially as a source of tin (cassiterite). There are currently two mines in operation, Bikita and Al. Hayat, together creating the world's fourth largest supplier of lithium. The private owner of Bikita Minerals does not provide current data on the size of the resource, but according to random information, it is estimated at about 11 million tonnes of ore. Examination of another large spodumene pegmatite, located nearby, with an estimated resource of 13 million tonnes of mineral (1.6%  $\text{Li}_2\text{O}$ ) is ongoing (Goodenough et al. 2021). In addition, several other areas are being examined in Zimbabwe by Zimbabwe Lithium and Zimbabwe Mining Development Corp.: Arcadia east of Harare (resource estimate 37.4 million tonnes/1.22%  $\text{Li}_2\text{O}$ ), and Zulu (near Bulawayo, resource estimate 20.1 million tonnes/1.06%  $\text{Li}_2\text{O}$ ) (Next et al. 2019). The possibility of recovering lithium from the tailings of the Kamativi pegmatite exploited between 1936 and 1994 (resources of about 26.32 million tonnes with  $\text{Li}_2\text{O}$  content – 0.58%) is also being investigated (Goodenough et al. 2021).

Pegmatite deposits in China occur in the Mongolian Altai, Inner Mongolia, Tien Shan, and western Yunnan, as well as isolated deposits in India and Mongolia. The largest and most developed are: Yichun in Jiangxi province and Jiajika in Sechuan province, with reserves ca. 80.5 million tonnes of lithium ore, grading 1.28% Li (Evans 2008). Moreover, there are numerous deposits of lithium-bearing muscovite granites which, apart from lithium (lepidolite), also contain tin, tantalum and fluorite, as well as greisen deposits enriched in lithium.

Considerable raw material potential also exists in Russia (Siberia, the Altai Mountains and the Kola Peninsula), where several dozen deposits have been identified. The biggest are: Alakshinskie, Tastyg, Vishniakovskie (Kavanagh et al. 2018).

In South America, the largest deposits are located in Brazil in the vicinity of the tectonic seam of the East Brazilian Shield. They occur in two regions: in the Jequitinhonha Valley in the state of Minas Gerais (developed Volta Grande deposit) and in Indianapolis county. Smaller deposits are known from Argentina (Cordoba and St. Luis provinces).

## 1.2. Lithium-bearing brines

The longest tradition of lithium chloride recovery from brines is associated with the Silver Peak deposit in the Clayton Valley area of Nevada (USA), where exploitation began as early as 1966. This lake has an area of 72 km<sup>2</sup> and its drainage area is 1342 km<sup>2</sup> (Brown et al. 2016). Lithium concentrations in brines here are the result of a complex history consisting of periods of evaporation, the mixing of waters of different origin, and dissolution and precipitation of halite and hectorite. Their original concentrations are thought to have been related to tectonic activity (presence of a fault) and the presence of thermal waters there (Garret 2004).

The largest accumulation of salt flats in the world is in South America, in the central Andes, in the zone of active volcanism at an altitude of more than 3500 m above sea level. The internal drainage zone of this area reaches 400,000 km<sup>2</sup>. There are about 150 separate pools and over 100 salt lakes and pans. The largest salt flat is the salt flat de Uyuni in Bolivia (Table 2, Figure 2). Including lakes Titicaca and Poopó, it constitutes the remains of the Pleistocene lake, Ballivián. Its area with a difference in elevation of only 41 cm, which makes it one of the flattest areas in the world. The surface of the salt flat is covered by a salt crust, under which there is a brine extremely rich in lithium. It is estimated that it may contain as much as about half of the world's lithium reserves and significant amounts of potassium and boron.

Table 2. Major salars in South America

Tabela 2. Ważniejsze solniska w Ameryce Południowej

| Name                   | Area (km <sup>2</sup> ) | Average lithium content in brines (ppm) |
|------------------------|-------------------------|---|
| Salar de Uyuni         | 10,582                  | on average 250                          |
| Salar de Atacama       | 3,000                   | 1,000–4,000, on average 1,500           |
| Salar de Hombre Muerto | 565                     | 190–900, on average 500–600             |
| Salar de Olaroz        | 500                     | on average 500                          |
| Salar de Rincon        | 500                     | on average 330                          |

Source: based on (Brown et al. of 2016).



Fig. 2. Salar de Uyuni – the largest salt flat in the world  
Phot. B. Radwanek-Bąk

Rys. 2. Salar de Uyuni – największe solnisko świata

The largest deposit developed here since 1984 is Salar de Atacama (Chile) with an area of over 3,000 km<sup>2</sup> and a drainage area of about 11,800 km<sup>2</sup> (Table 2). The geysers of the El Tatio field (one of the largest in the world) to the north of the salar are considered the main source of lithium. These waters feed the Rio del Salado and then the Rio San Pedro, remaining in the drainage zone of the salt flat. Additional amounts of lithium are provided by groundwater. In mine evaporation tanks, the average lithium content is about 1,500 ppm (Garret 2004). Smaller but also extensive areas are occupied by other salt flats of South America. In addition to the listed one, the following are also developed: Salar de Hombre Muerto, Salar de Olaroz and Salar de Rincon (Table 2), all of them in Argentina.

A significant accumulation of salt flats occurs in China, in two major regions in western Tibet: (Zhabuye salt flat at more than 4,400 m above sea level) and in the Cajdam Basin (at 2,880–3,000 m above sea level). The entire Cajdam Basin is a drainless tectonic basin, covering an area of over 90,000 km<sup>2</sup>. There are twenty-eight separate salt lakes here and, in addition, brines have also been found in numerous dry near-surface salt pans. The largest lakes East and West Taiji Nai'er are located at 2,880 m above sea level and cover areas of 86 and 116 km<sup>2</sup>, respectively. The Zhabuye salt flat covers an area of about 240 km<sup>2</sup>. The mineral is lithium carbonate – zabuyelite. The resource estimate for the deposit is 1.53 million tonnes Li (8.3 million tonnes lithium carbonate) (Evans 2008). The average content of Li in brines is 0.1% Li (Bowell et. al. 2020).

The cost-effectiveness of developing lithium-bearing brine deposits is due to the fact that their deposits are large, favorable for simple open-pit mining, and lithium recovery is uncomplicated. Difficulties can include basin geometry, low lithium concentrations, seasonal variability in mining conditions, location on dry, poorly accessible land and resulting freshwater supply problems, and also the negative environmental impacts of large-scale mining.

### 1.3. Geothermal brines

Geothermal waters, geothermal brines are sometimes presented as a separate subcategory of potential lithium deposits, mainly due to the fact that so far no satisfactory technologies for their direct utilization have been elaborated. They probably occur in most geothermal areas in the world, but are initially recognized in: USA (Salton Sea), Iceland (Reykjavik area), New Zealand (Wairakei), Japan (on the island of Kiusiu), the Fiji Islands and Italy (Cesano) and France (Alsace). They contain from 12 to 350 ppm Li. The potential for lithium recovery in this case is related to their use as sources of renewable, “green” geothermal energy. This is currently how the Salton Sea thermal waters are used in California, where there are eleven power plants supplying over 370 MW of energy. The thermal waters of this region contain numerous metals including manganese, zinc and lithium in amounts in the order of 100–200 ppm (Brown et al. 2016).

### 1.4. Brines associated with hydrocarbon fields

The second recently identified subcategory of brines are those that accompany hydrocarbon deposits. Until now, they have mostly been considered unusable and re-injected into the rock mass. Occasionally, however, they may contain significant amounts of lithium and other elements such as bromine, which is potentially recoverable. An example is the Smackover oil field (Arkansas, USA). Lithium concentrations in excess of 500 ppm have been found in the surrounding brines at depths ranging from 1,800 to 4,800 m (Garret 2004). Bromine has been recovered on a large scale from this brine at the Magnolia plant owned by Albemarle (the world’s largest producer) since 1969. In 2010, efforts were made to develop the technology and construct a pilot lithium recovery plant (Brown et al. 2016). Sparse reports so far indicate that the first batches of lithium carbonate were obtained in 2020 and commercial recovery is planned soon.

### 1.5. Lithium-bearing clays

Lithium bearing clays are most commonly found in large volcanic craters. Their main useful mineral is hectorite, discovered in Hector, USA (California). It is mined on a small scale from the Kings Valley deposit located within the large Mc Dermitt caldera on the Nevada-Oregon border. Measured resources here amount to over 7 million tonnes of mineral at 0.457% Li, indicated resources amount to 8 million tonnes (at 0.435% Li) and inferred resources amount to a further 7 million tonnes (0.416% Li) (Brown et al. 2016). Bentonite and especially hectorite are mainly used in the petroleum industry (drilling muds) but more recently also as a source of lithium. Mining and processing is carried out by Lithium Americas Co. Significant hectorite resources have also been found in the Sonora desert in northern

Mexico. A mine and a pilot processing plant focused on lithium carbonate production have been established here. Concentrations of hectorite have also been found in the Bigadic borate deposit in Turkey (Helwaci et al. 2004).

Jadarite which belongs to the zeolite group, is the latest of the known sources of lithium. It was found in 2007 in the Jadar Basin in Serbia, where the only deposit of it in the world to date has been documented. Jadarite occurs here both in its massive form, forming a layer over 7-meters thick, and in the form of nodules in a fine-grained carbonate matrix. The inferred resources of the deposit are estimated to be over 125 million tonnes of mineral with an average  $\text{Li}_2\text{O}$  content of 1.8% (Brown et al. 2016). Lithium is accompanied by boron. Rio Tinto is the main company operating here. Operations are scheduled to begin in 2025.

## 2. World resources of lithium minerals

The total global documented resources of lithium are estimated according to the latest USGS data at over 86 million tonnes Li (Jaskula 2021), and (reserves) at about 21 million tonnes. Over a period of 5–8 years, the lithium resource has almost doubled as a result of intensive exploration. To illustrate this, Table 3 summarizes the estimates provided by BGS (Brown et al. 2016) based on earlier data from Evans of 2014 and the USGS (Jaskula 2021). These data are partially incomplete, as for some countries only the known reserves of the largest deposits are given, for others it is the total estimates of many.

In general, continental brine deposits – of which 170 have been discovered – dominate in terms of quantity, followed by pegmatite deposits (138), then lithium-bearing clay deposits (37), brines associated with hydrocarbon deposits (35), and geothermal brines (9) (Cronwright 2019). These quantities change dynamically with new discoveries.

## 3. Extraction methods and processing

Pegmatite lithium mineral deposits are mined using traditional mechanical or blasting methods. Opencast mines predominate, but underground mines are also active. The output is subjected to traditional enrichment (crushing, separation of lithium minerals and their concentration, using the heavy liquid flotation method). The products are concentrates, mainly spodumene or lepidolite. Thermal methods are used less frequently. Typical concentrates used later in the production of lithium carbonate contain 6–7%  $\text{Li}_2\text{O}$  i.e. 75–87% spodumene), while the higher purity concentrates used in the ceramic industry contain more than 7.6%  $\text{Li}_2\text{O}$  and a lower iron content.

Continental brine deposits are exploited by pumping brine and evaporating it in suitable basins, from where the material is directed to a processing plant where oxide, chloride or carbonate is obtained. In the majority of deposits, the evaporation process consists of several stages, due to the recovery of other substances: sodium chloride and potassium chloride or

Table 3. Global lithium resources

Tabela 3. Światowe zasoby litu

| Country          | Deposits type      | Amount of deposits | Resources (thousand Mg Li) 2014/2021 | Share of global resources 2020 (%) |
|------------------|--------------------|--------------------|--------------------------------------|------------------------------------|
| Bolivia          | continental brines | 1                  | 8,900/21,000                         | 24.3                               |
| Chile            | continental brines | 3                  | 7,100/9,600                          | 11.0                               |
| USA              | sub-total          |                    | 6,720/7,600                          | 8.7                                |
|                  | pegmatites         | numerous           | 2,830*                               |                                    |
|                  | hectorite          | 1                  | 2,000*                               |                                    |
|                  | geothermal brines  | 1                  | 1,000*                               |                                    |
|                  | oilfield brines    | 1                  | 850*                                 |                                    |
|                  | continental brines | 1                  | 40*                                  |                                    |
| Argentina        | continental brines | 6                  | 6,520/19,300                         | 22.3                               |
| China            | sub-total          |                    | 3,350/5,100                          | 5.8                                |
|                  | continental brines | numerous           | 2,600*                               |                                    |
|                  | pegmatites         | numerous           | 750*                                 |                                    |
| Congo (Kinshasa) | pegmatites         | 1                  | 2,300/3,000                          | 3.4                                |
| Australia        | pegmatites         | 3                  | 1,683/6,400                          | 7.4                                |
| Russia           | pegmatites         | numerous           | –/1,000                              | 1.1                                |
| Canada           | pegmatites         | 3 mains + others   | 977/2,900                            | 3.3                                |
| Germany          | pegmatites         | a few              | –/2,700                              | 3.1                                |
| Mexico           | hectorite          | 1                  | 180/1,700                            | 1.9                                |
| Czech Republic   | pegmatites         | a few              | –/1,300                              | 1.5                                |
| Serbia           | jadarite           | 1                  | 950/1,200                            | 1.2                                |
| Peru             | pegmatites         | a few              | –/880                                | 1.0                                |
| Mali             | pegmatites         | a few              | –/700                                | 3.0                                |
| Zimbabwe         | pegmatites         | a few              | 56.7/500                             |                                    |
| Other**          | pegmatites         | numerous           | –/970                                |                                    |

\* 2014.

\*\* Resources below 500 thousand tonnes: Spain, Portugal, Brazil, Ghana, Austria, Finland, Kazakhstan and Namibia.

Source: [Brown et al. 2016](#), based on previous data: [Evans 2014](#).

sulphate, borates, magnesium carbonate (they precipitate from solutions earlier than lithium compounds). Due to the degradation of aquifers by pumping huge amounts of brine, a method of lithium recovery has been developed without evaporation, which makes it possible to re-inject brine into the rock mass or use it for industrial or agricultural purposes (which is not recommended for ecological reasons – renewal of water resources).

Deposits of lithium-bearing clays are mined using opencast methods and excavated mainly mechanically, due to the low hardness of the rock. Lithium extraction is performed in two phases. The first, so-called dry phase involves crushing and mixing with added reactants (anhydrite and dolomite), followed by calcination. The second is leaching in water at 70°C in order to obtain brine, from which lithium carbonate is obtained at the final stage.

The recovery of lithium from unconventional brines is still in the trial stage, thus there is no information on the methods used.

The main products obtained in the enrichment and processing of all types of lithium minerals are lithium carbonate and hydroxide, which account for more than 90% of the total lithium raw materials. Lithium metal is obtained by electrolysis of a mixture of liquid lithium chlorides (40–60% LiCl) and potassium (Garret 2004).

#### 4. Application and structure of consumption of lithium raw materials

Applications of lithium raw materials are related to its electrochemical activity (the highest among alkali metals). Due to their properties, these raw materials have found numerous applications e.g. (Bilans 2015):

- ◆ Lithium carbonate and hydroxide – this is used in the manufacture of rechargeable batteries and battery packs.
- ◆ Lithium carbonate – this is used in the manufacture of glass and ceramics, as well as in steel and aluminum metallurgy (by lowering the melting temperature, it contributes to a significant improvement in process efficiency, energy savings and – indirectly – the reduction of fluorine emissions to the atmosphere).
- ◆ Lithium hydroxide – this is used as a component of lubricants (extends the range of their application temperatures, improves resistance to moisture and oxidation, thanks to which it is valued in the military, aviation, automotive and shipbuilding industries).
- ◆ Lithium metal – this is mainly used as a component of aluminum and manganese alloys (increases their mechanical strength and hardness). These alloys are widely used in the aerospace industry. It is sometimes introduced into lead-bearing alloys. It is a strong desulphuriser and deoxidiser in copper refining, also in the casting of copper alloys and silver binders and serves as a coolant in nuclear technology.
- ◆ Lithium niobate and lithium tantalate – due to the fact that they form ferromagnetic crystals, they are used in electroacoustic devices.

Other important fields of use of lithium compounds are (Bilans 2015) the plastics industry (abrasion-resistant synthetic rubbers, thermoplastic rubbers, polyethylene), the pharma-

ceutical industry (production of, among others, vitamin A, steroids, analgesics, sedatives and sleeping pills) and the cosmetics industry (role of catalysts).

The share of individual directions of lithium applications in the structure of world consumption has changed significantly in recent years. The dynamically growing demand in the electrical-engineering industry (production of batteries and battery packs) has caused this to already account for 71% of world consumption (most frequently in the form of carbonate and hydroxide), the share of the glass and ceramics industry (mainly heat-resistant vessels and ceramic hotplates) amounts to 14%; the production of lubricants accounts for 4%; 2% each for continuous casting of steel and production of polymers; 1% each for air-conditioning and refrigeration and Al metallurgy (Figure 3). Of these, the biggest growth opportunities are still related to the production of lithium and lithium-ion batteries and battery packs, especially their new generation with extended life for recharging, for electric and hybrid cars, for portable electronic devices as well as in energy storage (Jaskula 2020).

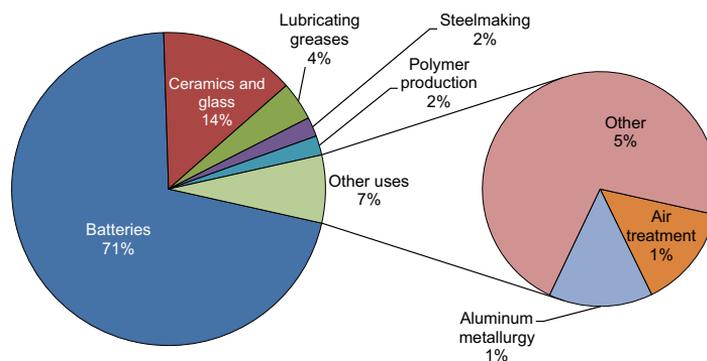


Fig. 3. Consumption of lithium raw materials in the world in 2020

Source: based on data (Jaskula 2020, 2021)

Rys. 3. Struktura zużycia surowców litu na świecie w 2020

## 5. World production and prices of the main lithium raw materials

The supply of lithium raw materials in the world in 1999–2008 increased by 56% in total and reached almost 58 thousand tonnes  $\text{Li}_2\text{O}$  (Figure 4). This growth was a response to the development of demand from developed countries by the glass industry, the ceramics industry, and mainly the development of rechargeable lithium-ion battery production. In 2009, there was a correction of the upward trend, related to the global financial crisis, which caused a general economic slowdown and even recession in some countries. Faced with this situation, manufacturers in Chile and Australia (the world's major manufacturers), as well as in Argentina and Canada, significantly reduced production, and the global supply consequently fell by almost 25% to 43.6 thousand Mg  $\text{Li}_2\text{O}$  in 2009.

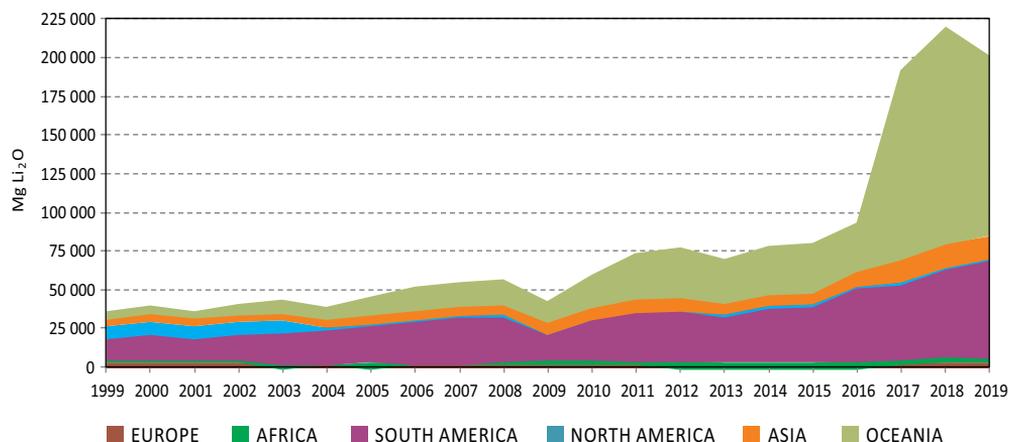


Fig. 4. Geographical structure of the global production of lithium raw materials  
 Source: own study based on data (Jaskula 2020; WMP 2021)

Rys. 4. Struktura geograficzna światowej produkcji surowców litu

Between 2010 and 2012, the global supply of lithium raw materials increased again, by a total of 79%, reaching a record 78.1 thousand Mg Li<sub>2</sub>O (Figure 4). This basically developed in two countries Chile and Australia and to a lesser extent in China. Other manufacturers have either restored supply to pre-crisis levels or even reduced it (e.g. Brazil and Argentina). The recorded increase in the production of lithium raw materials in the world was a response to the development of demand from highly developed countries, advanced primarily in the manufacture of rechargeable lithium-ion batteries and battery packs, and to a lesser extent in the glass and ceramics industries. Battery production has been dominated by Asian countries, particularly China, Japan and South Korea. However, in 2013, due to reduced demand from major consumers, the upward trend in lithium raw-material supply was halted, with global production declining by nearly 10% in total. Almost all global manufacturers reduced supply (except for Argentina) and the largest declines were recorded in China, Chile and Australia, amounting to 22%, 15% and 12%, respectively (Figure 4). Between 2014 and 2016, the global demand for lithium raw materials was again increasing steadily, followed by supply, which increased by a total of 33%, with some manufacturers, such as Zimbabwe and the US, not increasing production (Figure 5).

The increasing interest of the automotive industry in the second decade of the twenty-first century to produce electric cars (hybrid or fully electric) resulted in a spectacular increase in the demand for rechargeable lithium battery packs in 2017–2018, which were found to be the most stable energy source for such vehicles. As a result, in those two years alone, the production of lithium raw materials more than doubled to a record level of 221.3 thousand Mg Li<sub>2</sub>O (Figure 5).

Virtually all manufacturers expanded production and the largest increase, almost four and a half times, was recorded in Australia. In 2019, production in Australia was cut by

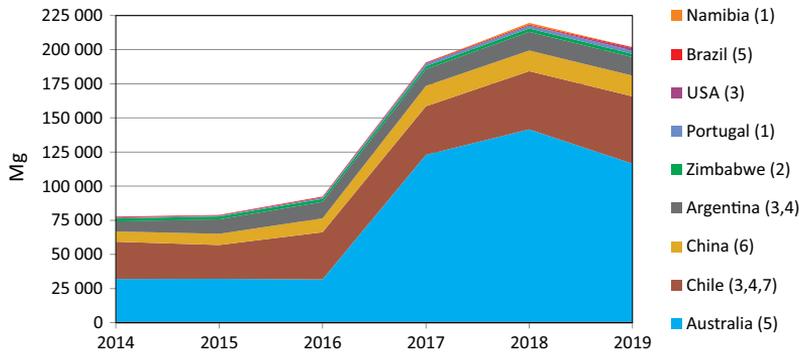


Fig. 5. World production of lithium (Mg Li<sub>2</sub>O)

(1) – lepidolite, (2) – amblygonite, lepidolite, petalite and spodumene, (3) – lithium carbonate from brines, (4) – lithium chloride, (5) – spodumene concentrate, (6) – lithium carbonate, (7) – lithium hydroxide

Source: own study based on data (Jaskula 2021; WMP 2021)

Rys. 5. Światowa produkcja surowców litu (Mg Li<sub>2</sub>O)

17%, despite continued production expansion in Chile, China and Portugal, and consequently global supply decreased to 201.5 thousand Mg Li<sub>2</sub>O (see Figures 4, 5). It can be noted that, in principle, only manufacturers of lithium mineral concentrates from pegmatite deposits (e.g. in Australia) are able to significantly increase supply within a relatively short period of time (one or two years) in response to increased customer interest, whereas manufacturers of lithium raw materials from brines, e.g. in Chile, cannot demonstrate such flexibility to increase supply (see: Figure 5).

In recent years, the largest manufacturers of lithium raw materials in the world have been Australia, Chile, China, Argentina, Zimbabwe and Portugal, with Australia's production in the last three years accounting for more than 50% of world supply (Figure 5). In Australia, pegmatite deposits are mined (Greenbushes, Mt Cattlin, Mt Marion, Wodgina) from which spodumene concentrates are produced. In Chile (Salar de Atacama) and Argentina (Salar de Hombre Muerto, Salar Cauchari – Olaroz and Salar de Rincon) lithium raw materials are extracted from lithium-bearing brines. In China, numerous pegmatite deposits (e.g., the Jiājīka), brine deposits (Zhabuye, Tiāji Nà'èr), and in Zimbabwe pegmatite deposits (Bikita and Manono-Kitololo), are dynamically developed.

Companies present in the lithium raw materials market have been undergoing a number of ownership changes in recent years, as a result of mergers and acquisitions. Chinese companies are very active in this regard, with significant capital coming from the internal market. Capital in China is accumulated thanks to the concentration of the potential for processing lithium raw materials and manufacturing finished products, e.g. batteries and battery packs. Leading companies conduct both the mining and processing of lithium raw materials. Currently, the largest companies globally are Jiangxi Ganfeng Lithium (China) – holding interests in the Mt Marion and Wodgina spodumene deposits in Australia (through a joint venture with Australian Mineral Resources), also exploiting the Ningdu spodumene deposit in China, as well as brine

deposits Zhabuye in China and Mariana and Cauchari-Olaroz in Argentina (along with Chile's SQM and Lithium Americas Corp.). The extracted spodumene concentrates from Australia and lithium compounds from Argentina are transported to numerous plants in China, where lithium carbonate, lithium hydroxide and lithium metal (the world's largest producer) are produced ([Ganfenglithium 2021](#)). The second largest producer of lithium-bearing raw materials is the US company Albemarle – it sources lithium raw materials from brines at the Salar de Atacama deposit in Chile (a joint venture with Chilean company Sociedad Quimica y Minera de Chile S.A – SQM and from 2019 with Sichuan Tianqi Lithium, currently the world's third largest producer of lithium raw materials), Silver Peak in the US, and spodumene concentrates from the Greenbushes deposit in Australia (again a joint venture with Sichuan Tianqi Lithium). Albermale produces lithium carbonate and lithium hydroxide at its La Negra plant in Chile and Silver Peak plant in the US, and lithium metal at its Langelsheim plant in Germany ([Albermale 2021](#)). Sichuan Tianqi Lithium produces lithium compounds and lithium metal at numerous plants in China and the newly opened Kwinana plant in Australia produces hydroxide ([Tianqilithium 2021](#)). The aforementioned Chilean company (SQM), currently the fourth largest producer of lithium raw materials in the world, produces lithium carbonate and lithium hydroxide at its Salar del Carmen plant on the coast near Antofagasta, using brines extracted from the Salar de Atacama deposit ([SQM 2021](#)). Another important producer is the Australian company Mineral Resources, whose activities include the open-pit mining of lithium ores (Mt Marion and Wodgina pegmatite deposits) and their processing into lithium hydroxide ([Mineralresources 2021](#)). Smaller manufacturers of lithium concentrates include: FMC Lithium Corp. (Salar de Hombre Muerto), Canadian company Rincon Ltd. (Salar de Rincon), Bikita Minerals in Zimbabwe (the world's largest producer of petalite, a subordinate of spodumene concentrates), and Sociedad Minería De Pegmatites in Portugal (a supplier of crude lepidolite). In Brazil, spodumene concentrates are produced by Companhia Brasileira de Lítio from the Cachoeira deposit, and also by CIF Mineração S.A. (Volta Grande mine).

A project to develop an open pit mine in the Manono-Kitololo (DRC) area focused on the extraction and recovery of lithium and tin was completed in 2020. This project was led by AVZ Minerals (65% shares) together with the Congolese state-owned company La Congolaise D'Exploitation Minière of the DRC (25%) and Dathcom Mining (15%). The mine is scheduled to open in late 2021. Investors have already signed long-term contracts with several Chinese companies (Ganfeng Lithium and YibinTianyiLithium Industry) for spodumene concentrate supply ([Goodenough et al. 2021](#)).

The balance of power on the lithium raw-material market may change with the entry of Bolivia. Advanced work is underway on the start-up of large-scale mining from the Salar de Uyuni, as well as its processing and, in the longer term, the construction of a battery factory. Mining is carried out by the state-owned Corporation Minera de Bolivia, while the accompanying investment projects are also carried out by the state-owned company GNRE. The Bolivian government, which controls mining and processing activities, is very reluctant to allow the presence of foreign investors, with small-scale cooperation (processing) with China and Germany ([Szczesniak 2017](#)).

Manufacturers of lithium compounds also include countries without their own resource base, relying on imports (mainly of lithium carbonate), such as France, Germany, Japan, South Korea, Taiwan and the United Kingdom.

## 6. Foreign trade turnover and prices

Technical lithium carbonate ( $\text{Li}_2\text{CO}_3$ ) containing 40%  $\text{Li}_2\text{O}$  and lithium hydroxide (produced from carbonate), which have become the main raw materials for lithium-ion batteries and battery packs, are the dominant internationally traded raw materials. In recent years, the commercial importance of lithium mineral concentrates such as lepidolite, spodumene, petalite, amblygonite, which dominate in glass and ceramic applications, where they replace carbonate, has declined. This is due to the potential for significant cost reductions in concentrate supply compared to carbonate (by 60% per tonne of Li). It is not possible to balance the volume of the export and import of lithium-bearing raw materials due to the fragmentary nature of statistical data.

The leading exporters of lithium raw materials include (Worldbank 2021) Australia, Zimbabwe, Portugal and Brazil for concentrates, Chile, Argentina, USA, Germany and China for carbonate and hydroxide, and importers only from developed countries are USA (e.g., in 2018 imports of 17.2 thousand Mg of carbonate and 1.1 thousand Mg of hydroxide), Japan (2019: imports of 23.5 thousand Mg of carbonate and 37.3 thousand Mg of hydroxide), South Korea (in 2018 imports of 33.2 thousand Mg of carbonate and 23.5 thousand Mg of hydroxide), Canada, Germany, France, Italy, the United Kingdom and other Western European countries and, in recent years, China (in 2018 imports of 24.5 thousand Mg of carbonate and 5.0 million tonnes of spodumene concentrates) and India (in 2018 imports of 1.9 thousand Mg of hydroxide).

Prices of individual lithium raw materials fluctuated within a wide range reflecting changes in international markets. Lithium raw material price quotations had two phases from 1999 to 2019. The first one concerns the years 1999–2013, when global sources provided regular price quotations, in deliveries to the USA market of both lithium concentrates – petalite and spodumene (in two types) and lithium carbonate (Figure 6). From 2014 to 2019, price quotations for lithium mineral concentrates were no longer officially reported. This was due to the change of their main purpose – they have become an important raw material for the production of lithium carbonate for use in the battery industry – in view of the decreasing demand of the ceramic and glass industries, their previous main users. During this period, lithium carbonate prices were regularly quoted.

Between 1999 and 2013, the smallest price fluctuations occurred for petalite concentrates, which varied within a narrow range of USD 250–270/tonne (Figure 6). The spodumene concentrates, both 7.2%  $\text{Li}_2\text{O}$  content and the glass grade, were subject to similar changes reflecting the changing demands of the glass and ceramics industries. In general, they were stable from 1999 to 2005 with a decreasing trend, especially for concentrates with high

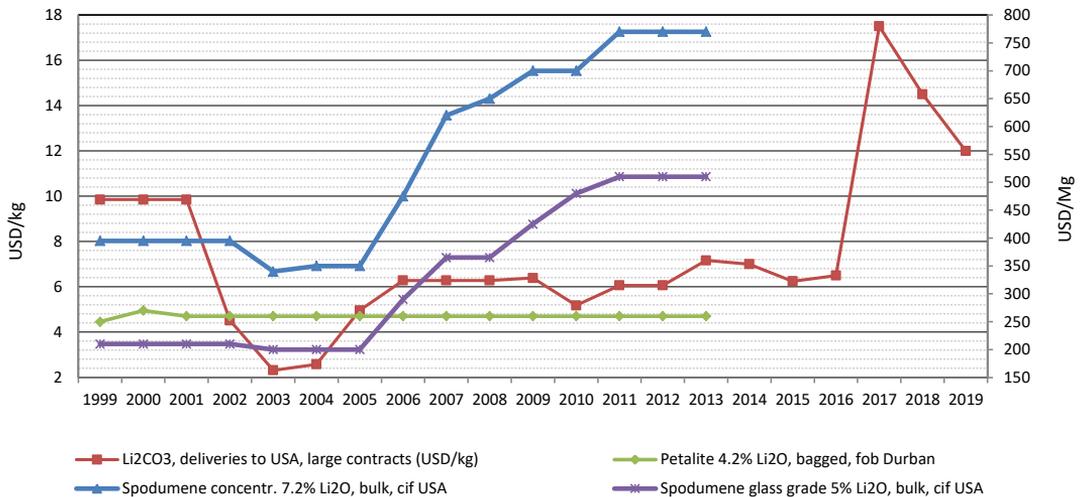


Fig. 6. Lithium raw material prices in 1999–2019  
 Source: own study based on data (Industrial Minerals 2014–2019)

Rys. 6. Ceny surowców litu w latach 1999–2019

Li<sub>2</sub>O content. Prices rose sharply between 2005 and 2009, by more than 200% in total, reflecting increased demand from customers before stabilizing between 2010 and 2013, reaching USD 770/tonne for a concentrate with 7.2% Li<sub>2</sub>O content, with the glass grade costing USD 510/tonne (Figure 6).

Prices of lithium carbonate, supplied to the U.S. market from abroad, remained high at nearly USD 10/kg from 1999 to 2001. In 2002–2005, the prices of this raw material were subjected to strong pressure from new manufacturers from Chile and Argentina who, by entering the market, increased global supply leading to a sharp drop in prices, in total by as much as 400% in total in that period (see: Figure 6). Between 2006 and 2016, the lithium carbonate market stabilized with relatively mild price movements and fluctuations within a fairly narrow range of USD 5.2–7.2/kg. In 2017–2019, the rapid growth of the electric-car market resulted in an extraordinary increase in demand for lithium carbonate, resulting in prices first increasing by 270% in 2017 to a record level of USD 17.5/kg, followed by a correction in price quotations in 2018–2019, with increased global production causing an oversupply in the market, which, combined with a lower growth rate in electric car sales than expected, especially in 2019, led to a cumulative price decline to USD 12/kg in 2019 (see: Figure 6). It is worth noting that in 2016–2019, China became the world's main buyer of lithium raw materials, resulting in price indices for these raw materials for the Chinese market only, often expressed in local currency instead of the commonly used US dollar.

## 7. Management of lithium raw materials in Poland

There are no lithium mineral deposits in Poland; therefore, lithium raw materials are not produced and the entire domestic demand is covered by imports. Various types of evaporites have been studied for this purpose in the past (Garlicki et al. 1991) pegmatites of the northern surrounding of the Karkonosze Mountains (Kozłowski 2002), waters and brines pumped out during drainage of coal and copper ore mines (Fijałkowska et al. 2008), waters associated with hydrocarbon deposits (Uliasz-Misiak 2016), and more recently Permian zubers associated with rock salt (Tomassi-Morawiec et al. 2019). None of these or similar occurrences are depositional in nature. Lithium oxide, hydroxide and lithium carbonate are the main lithium raw materials imported to Poland (Figure 7).

In the period 2014–2019, these raw materials were imported in quantities of 100–200 t/y in the case of oxide and hydroxide, while purchases of lithium carbonate in this period were slightly higher with volumes ranging between 137 tonnes and 218 tonnes/year (Figure 7). The largest suppliers of lithium raw materials to Poland in this period were Chile (main supplier of lithium carbonate), European Union countries (re-exporters), the United States, Russia (main supplier of lithium oxide and hydroxide – also re-exporter) and China. The export of these raw materials is much smaller compared to import and in 2014–2019, reached volumes of 13–33 t/y for both raw materials (Figure 8) and was directed mainly to Russia, Ukraine and Hungary. The domestic demand for lithium oxides and hydroxides from 2014 to 2019 (calculated here as apparent consumption) ranged from 88.1 tonnes in 2015 to 182.7 tonnes in 2019, averaging 110.4 t/y over the period. By contrast, the demand for lithium carbonate (also calculated as apparent consumption) in 2014–2019 was slightly higher than for Li oxides and hydroxides and ranged between 121–196 Mg/y (see: Figures 7, 8), averaging 146.4 Mg/y.

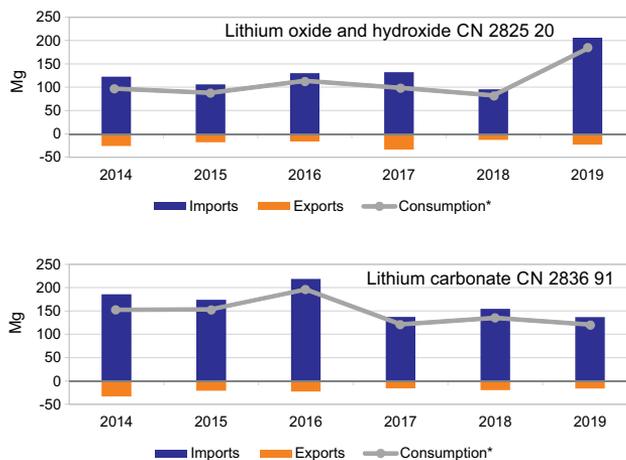


Fig. 7. Lithium statistics in Poland (in tonnes)  
 Source: own study based on data (GUS 2021)

Rys. 7. Gospodarka surowcami litu w Polsce (w tonach)

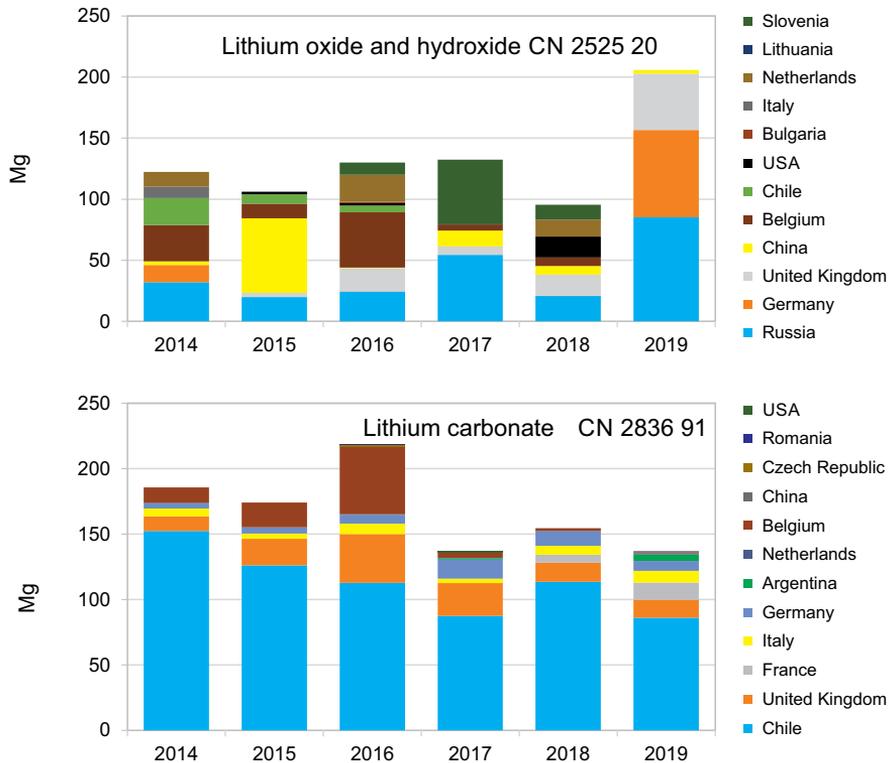


Fig. 8. Geographical structure of import of lithium raw materials to Poland (in tonnes)  
 Source: own study based on data (GUS 2021)

Rys. 8. Struktura geograficzna importu surowców litu do Polski (w tonach)

Lithium oxides and hydroxides imported to Poland are mainly used in the glass, ceramic and electronics industries, but no further information on the detailed structure of their use is available (MYP 2015). Other important fields of application of lithium compounds include plastics and pharmaceutical industries. However, this structure may change completely in the nearest future, as Poland has in recent years become one of the major manufacturers of batteries and battery packs in Europe, including those intended for use in hybrid and electric cars. There are currently over sixty companies operating in this sector in Poland, including world leaders such as Exide, Panasonic, LG, Sznajder and others. Moreover, other battery and battery-pack factories dedicated strictly to applications in electric cars are being built, among others by Umicore, Northvolt and Daimler. A potential change in the structure of lithium raw-material consumption in Poland may cause the battery and battery-pack sector to consume over 90% of these raw materials in the country and its volume may increase by even two or three orders of magnitude. However, such a change is not a foregone conclusion, as manufacturers of lithium-ion batteries may import finished components or semi-finished products instead of manufacturing these intermediates from imported raw lithium oxides

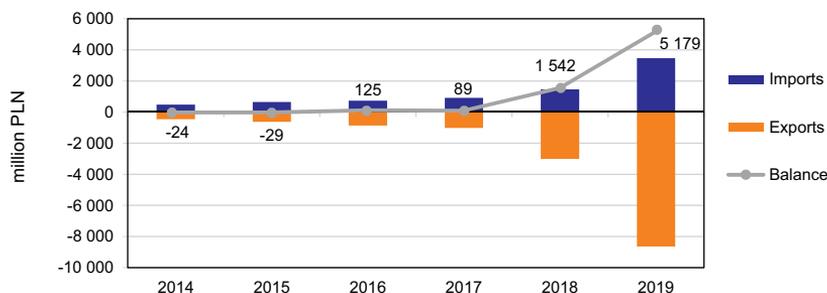


Fig. 9. Value of lithium-ion batteries trade (CN 8507 60) in Poland (in million PLN)

Source: own study based on data (GUS 2021)

Rys. 9. Wartość obrotów bateriami litowo-jonowymi (CN 8507 60) w Polsce (w mln PLN)

and hydroxides. Consequently, only activities consisting in the assembly of finished products from semi-finished products will be carried out in Poland.

Symptoms that attest to such a development of the structure and volume of Li oxide and hydroxide consumption is the fact that the production as well as the export of lithium-ion batteries recorded by the Central Statistical Office statistics is growing much faster than the import of raw Li oxides and hydroxides used in their production. The value of exports in 2018–2019 was growing at a rate of almost 300%/year (Figure 9).

In 2020, the upward trend continued. According to a report by the National Bank of Poland, the value of exports amounted to a record level of PLN 17.8 billion, and in Q4, alone it reached PLN 7.6 billion (Ciepiela 2021). Thus, Poland (and more specifically foreign companies operating in Poland) is currently the largest exporter of lithium-ion batteries in the European Union. The main recipients of Li-ion batteries manufactured in Poland in recent years have been countries with a developed automotive and electrical industry – Germany (over 44% of export value), France, Belgium, Sweden and Austria.

In the European Union, the main applications of lithium carbonate are similar to the global applications, but an increased share of its consumption is recorded in the aluminum smelting industry (mainly due to restrictions on fluorine emissions to the atmosphere). It is also worth mentioning that already in 2018 the European Commission has approved a strategy for the development of battery production in Europe, in which it takes into account the optimization of the battery value chain while respecting EU directives on environmental impacts, sustainable economy and labor matters (Batteries 2019).

## 8. Prospects for the development of the lithium raw-material market

The global prospects of the lithium raw-material market are extremely optimistic for the years 2020–2025. It is forecast that the boom in lithium-ion batteries will continue, and the development of electromobility, supported by incentives and subsidies for the purchase of

such vehicles by governments in many countries around the world, will result in an increase in demand, primarily for lithium carbonate and also for lithium hydroxide, by up to three times. Demand for batteries in Europe will grow rapidly in the coming years. According to estimates by the Brussels-based NGO Transport & Environment (T&E), it will be around 300 GWh in 2025, 700 GWh in 2030, and over 1300 GWh in 2035. Most of the new production capacities will be built in Germany (CATL investment projects), which may overtake Poland in this field by as early as 2024. Battery factories will also be built in other European countries, including Hungary, Norway, Sweden and France (Raport 2021). In the next decade alone, lithium consumption for electric vehicle (EV) production will increase from 50,000 Mg in 2020 to about 200,000 Mg in 2030, and by 2050, it could increase by as much as 500% compared to 2018 (Raport 2021).

Some market analysts, however, are a bit more skeptical, pointing out that in addition to lithium batteries, other types of batteries are also produced (e.g. nickel and cadmium) and there is continuous work on the development of new, even more efficient devices (e.g. polymer batteries HATN or PHATN) or alternative energy sources. Research on very efficient new generation lithium batteries, in which a solid polymer is used as an electrolyte and the anode is lithium, is advanced (Electromobilitypoland 2021).

## 9. Recycling and substitution

The need to develop lithium recycling or substitution has so far made little economic sense, due to its high cost and availability from primary sources.

In view of the dynamic increase in the number of electric vehicles in the world in recent years and set to come in the next few years, not only the demand for lithium will increase in the near future, but also the amount of used batteries and battery packs will grow significantly or even by leaps and bounds. In 2020 there were already 62 thousand Mg (The lithium giant 2021). Thus, they will constitute a significant component of environmentally hazardous waste and, at the same time, a large potential secondary source of lithium. Therefore, the leading manufacturers of lithium raw materials (e.g. Albermale, USA) and companies from the automotive industry are carrying out intensive research towards the development or optimisation of lithium recovery technologies, which fits into the model of a circular economy (CE). The main global manufacturers of lithium from recycled batteries include: Toxo Inc. of Canada, operating since 1992 and with plants in British Columbia and Ohio (USA) since 2009 (Hamilton 2009); Umicore Battery Recycling focused on lithium-ion battery recycling with its main smelter in Hoboken (Belgium), as well as in Germany, USA and Canada. Elemental Holding, an important Polish recycling company, has also announced an investment project in this area. The company has obtained a grant from the Ministry of Science and Higher Education to establish a recycling plant for used lithium-ion batteries. The new plant is to be built in Zawiercie and will process 10 thousand Mg of batteries and catalysts per year (Ebrd 2021). In addition to the recycling of lithium ion batteries and battery packs,

lithium is also increasingly recovered from a variety of mining and enrichment waste from tin, tantalum and borate ores. Rio Tinto, for example, has launched lithium recovery from the borate production waste in California in recent years. The heaps stored there are expected to supply 5,000 Mg Li/y, which covers the demand for the battery production of 70,000 electric vehicles. Lithium substitution, though possible, in its main applications (traditional batteries, glass and ceramics industries) is not yet economically viable. There are no substitutes for lithium for the production of lithium-ion batteries. They are replaced by a multitude of other types of battery.

## Conclusions

In recent years, we have noted a dynamic increase in the global demand for lithium raw materials. This is mainly related to the development of new directions of its use, especially in the automotive industry (batteries and battery packs), electronics, energy and nuclear weapons. In 2018 lithium was listed as a critical element for the US national security and economy (USGS 2021), and in 2020 it was also listed as a critical raw material for the EU economy (Eurostat 2021). This demand has been accompanied by a sharp increase in their supply – from around 79,000 Mg (2014) to over 200,000 Mg Li<sub>2</sub>O in 2020. The result of the development of supply and demand is a sharp increase in prices, which reached all-time highs between 2017 and 2020, except for petalite concentrate, the prices of which did not fluctuate. The main sources of lithium raw materials are primary sources. The leading position among them is currently occupied by lithium-bearing brine deposits. The supply of lithium raw materials coming from the aforementioned brine deposits overtook the supply from pegmatite deposits, which were the main source of lithium until the late 1990s. Deposits of lithium-bearing clays and jadarite are of secondary importance, whereas geothermal brines and brines accompanying hydrocarbon deposits are perspective. The growing demand for lithium raw materials has resulted in a number of new exploration and examination works, the resumption of production from some abandoned deposits, and the development of technologies for its recovery from secondary sources, mainly used batteries.

Lithium oxide and hydroxide and lithium carbonate are the main lithium raw materials used in Poland. In the absence of the country's own deposits, they are imported, in quantities of 100–200 Mg/year each. The main suppliers are Chile, Western European countries and Russia. Lithium raw materials imported to Poland are mainly used in glass and ceramic industries, as well as in electronics and other industries. However, this structure may change completely in the near future as Poland has become in recent years one of the major manufacturers of batteries and battery packs in Europe, including those intended for use in hybrid and electric cars. There are currently over 60 companies operating in this industry in Poland and the value of their exports in Q4 2020 alone reached PLN 7.6 billion. However, it seems that the development of lithium battery pack production does not affect the volume of lithium primary raw material consumption in the national economy. Lithium-ion-battery manufacturers seem to import

finished components or semi-finished products. Consequently, only activities consisting in the assembly of finished products from semi-finished products will be carried out in Poland.

*This paper has been prepared within the framework of the statutory activity of the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences in Kraków, Poland.*

## REFERENCES

- Avsminerals 2021. *Manolo Project*. [Online] <https://avsminerals.com.au/manono-mine> [Accessed: 2021-11-12].
- Albemarle 2021. [Online] <https://www.albemarle.com/> [Accessed: 2021-11-12].
- Batteries 2021. Batteries fit for Europe, 2019. Raport Advanced Rechargeable Lithium Batteries Ass. [Online] [www.rechargebatteries.org](http://www.rechargebatteries.org) [Accessed: 2021-11-12].
- Bilans 2015. *Balance of the economy of mineral resources in Poland and the world 2013 (Bilans gospodarki surowcami mineralnymi Polski i świata 2013)* Smakowski, T., Galos, K. and Lewicka, E. eds. Warszawa: PIG-PIB (in Polish).
- Bolewski et al. 1976 – Bolewski, A., Blaschke, W., Blaschke, Z., Pawlikowski, S., Smakowski, T., Wutcen, E. and Żabiński, W. 1976. *Minerals of the world Al-Be-Li-Mg, Lit (Surowce mineralne świata Al-Be-Li-Mg, Lit)*, pp. 225–271. Warszawa: Wyd. Geol. (in Polish).
- Bowell et al. 2020 – Bowell, R.J., Lagos, L., Camilo, R., de los Hoyos, Declerq J. 2020. Classification and characteristics of natural lithium resources. *Elements* 16, pp. 259–264. DOI: 10.2138/gselements.16.4259.
- Bradley et al. 2017 – Bradley, D.C., Stillings, L., W. Jaskula, B.W., Munk, L.A. and McCauley, A.D., 2017. *Lithium* [In:] *Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply*. USGS Prof. Paper 1802-K (eds. Schulz, K.J., DeYoung, J.H., Seal, II R., Bradley, D.C.), DOI: 10.3133/pp1802K.
- Brown et al. 2016 – Brown, T., Walters, A., Idoine, N., Gunn, G. and Shaw, R.A. 2016. *Lithium Profile*. British Geol. Survey. [Online] <https://www.bgs.ac.uk/news/mineral-profile-lithium/> [Accessed: 2021-11-12].
- Ciepiela, D. 2021. *Poland is the largest exporter of electric car batteries in the EU (Polska jest największym eksporterem baterii do samochodów elektrycznych w Unii)*. [Online] <https://www.wnp.pl/motoryzacja/polska-jest-najwiekszym-eksporterem-baterii-do-samochodow-elektrycznych-w-unii,468420.html> [Accessed: 2021-11-12] (in Polish).
- Cronwright, M. 2019. An Overview of Lithium: Geology to Markets. CAS Global Mining Industry Consultants. GS-SA-African Exploration Showcase 15 November 2019. [Online] [www.csaglobal.com](http://www.csaglobal.com) [Accessed: 2021-11-12].
- Dewaele et al. 2015 – Dewaele, S., Hulsbosch, N., Cryns, Y., Boyce, A., Burgess, R. and Muchez, P. 2015. Geological setting and timing of the world-class Sn, Nb-Ta and Li mineralization of Manono-Kitotolo (Katanga, Democratic Republic of Congo). *Ore Geology Reviews* 72, pp. 373–390, DOI: 10.1016/j.oregeorev.2015.07.004.
- Ebrd 2021. [Online] <https://www.ebrd.com>projekty>psd.51890> [Accessed: 2021-11-12].
- Electromobilitypoland 2021. [Online] <https://electromobilitypoland.pl> [Accessed: 2021-11-12].
- Eurostat 2021 – Critical raw materials [Online] [https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical\\_en](https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en) [Accessed: 2021-11-12].
- Evans, R.K. 2008. *An abundance of lithium*. World Lithium. Santiago, Chile.
- Evans, R.K. 2014. *Lithium* [In:] *Critical Minerals Handbook* (ed. Gunn, A.G.). Wiley and Sons, pp. 230–260.
- Fijałkowska et al. 2008 – Fijałkowska, A., Kurowski, R. and Czaplicka, M. 2008. The Polish raw material base of lithium in the context of global trends in the production of lithium carbonate from brines and lithium-bearing thermal waters (*Polska baza surowcowa litu w kontekście światowych tendencji produkcji węgla litu z solanek i litonośnych wód termalnych*). *Rudy i Metale Nieżelazne* 53(9), pp. 548–554 (in Polish).
- Ganfenglithium 2021. [Online] [http://www.ganfenglithium.com/about1\\_en.html](http://www.ganfenglithium.com/about1_en.html) [Accessed: 2021-11-12].
- Garlicki et al. 1991 – Garlicki, A., Szybist A. and Kasprzyk, A. 1991. Investigation of trace elements in salt deposits and chemical raw materials (*Badania pierwiastków śladowych w złożach soli i surowców chemicznych*). *Przełąd Geologiczny* 39(11–12), pp. 520–527 (in Polish).

- Garrett, D.E. 2004. *Handbook of Lithium and Natural Calcium Chloride, their deposits, processing uses and properties*. Elsevier Acad. Press. pp. 476.
- Goodenough et al. 2021 – Goodenough, K., Deady, E. and Shaw, R. 2021. *Lithium resources and their potential to support battery chains in Africa*. British Geol. Survey [Online] <http://nora.nerc.ac.uk/id/eprint/530698> [Accessed: 2021-11-12].
- GUS 2021. GUS – dane statystyczne za lata 2014–2019. [Online] <https://stat.gov.pl> [Accessed: 2021-11-12] oraz dane niepublikowane produkcji i obrotów handlu zagranicznego (*in Polish*).
- Hamilton, T. 2009. *Lithium battery recycling gets a boost*. *Technology Review*. [Online] <http://www.technologyreview.in/Energy/23215> [Accessed: 2021-11-12].
- Helvacı et al. 2004 – Helvacı, C., Mordogon, H., Çolak, M. and Gündogan, I. 2004. Presence and distribution of lithium in borate deposits and some recent lakewaters of west-central Turkey. *International Geology Review*, v. 46, no. 2, p. 177–190, DOI: 10.2747/0020-6814.46.2.177.
- Industrial Minerals* 2014–2019. [Online] <https://www.indmin.com/> [Accessed: 2021-11-12].
- Jaskula, B.W. 2020. *Lithium* [In:] USGS Minerals Yearbook – 2017. USGS Publ. Reston. Virginia.
- Jaskula, B.W. 2021. *Lithium* [In:] USGS Mineral Commodity Summaries: pp. 98–99. USGS Publ. Reston. Virginia, DOI: 10.3133/mcs2020.
- Kavanagh et al. 2018 – Kavanagh, L., Koehane, J., Cabellos, G.G., Lloyd, A. and Cleary, J. 2018. Global lithium sources – Industrial use and future in electric vehicle industry: a review. *Resources* 5(57), pp. 1–29, DOI: 10.3390/resources 7030057.
- Kozłowski, A. 2002. Lithium in rock-forming quartz in the northern contact zone of the Karkonosze massif SW Poland. *Mineralogical Society of Poland – Special Papers* 20, pp. 120–123.
- Krzak et al. 2021 – Krzak, M., Gałaś, A. and Król, K. 2021. Tantalum market at the beginning of the 21<sup>st</sup> century (*Rynek tantalu na początku XXI wieku*). *Przegląd Geologiczny* 69(4), pp. 234–243, DOI: 10.7306/2021.13 (*in Polish*).
- Kunasz, I. 2006. *Lithium resources* [In:] *Industrial Minerals and Rocks* (eds. Kogel, J.E., Tiverdi, N.C., Baker, J.M., Krukowski, S.T.), pp. 599–613. Soc. for Mining. Colorado. USA.
- The lithium giant 2021 – *The lithium giant focuses on recycling. The market is in for a surge in growth (Litowy gigant stawia na recykling. Rynek czeka skokowy wzrost)*. [Online] <https://www.wnp.pl/energetyka/litowy-gigant-stawia-na-recykling-rynek-czeka-skokowy-wzrost,468788.html> [Accessed: 2021-11-12] (*in Polish*).
- Mineralresources 2021. [Online] <https://www.mineralresources.com.au/> [Accessed: 2021-11-12].
- MYP 2015 – Smakowski, T., Galos, K. and Lewicka, E. eds. 2015. *Minerals Yearbook of Poland 2013*. Warszawa: PIG-PIB, 565 pp.
- Natkaniec-Nowak, L. and Słowakiewicz, M. 2010. Mineralogical-gemological and microthermometric studies of spodumenes from the Nilaw mine (Laghman Province, NE Afghanistan) (*Badania mineralogiczno-gemmologiczne oraz mikrotermometryczne spodumenów z kopalni Nilaw (Laghman, NE Afganistan)*). *Przegląd Geologiczny* 58(5), pp. 416–425 (*in Polish*).
- Next et al. 2019 – Next, P., Goodenough, K., Shawand, R. and Kinnaird, J. 2019. *A review of lithium occurrences in Africa*. British Geol. Surv., DST-NRF CIMERA (Centre of Excellence for Integrated Mineral and Energy Resources Analysis).
- Raport 2021 – *Raport organizacji Transport & Environment (T&E): Polska liderem produkcji baterii*. [Online] <https://www.teraz-srodowisko.pl/aktualnosci/transport-environment-ngo-raport-polska-liderem-w-produkcji-baterii-9987.html> [Accessed: 2021-11-12].
- SQM 2021. [Online] <https://www.sqm.com/en/> [Accessed: 2021-11-12].
- Szcześniak, P.A. 2017. *The minerals industry in Bolivia*. Washington: USGS Minerals Yearbook.
- Tianqilithium 2021. [Online] <http://en.tianqilithium.com/> [Accessed: 2021-11-12].
- Tomassi-Morawiec et al. 2019 – Tomassi-Morawiec, H., Wachowiak, J. and Czapowski, G. 2019. Comparative geochemistry and development of the Upper Permian (Zechstein) zuber rocks from Poland (*Geochemia i wykształcenie skał zubrowych górnego permu(cechsztyn) z obszaru Polski*). *Biuletyn PIG* 477, pp. 69–122, DOI: 10.7306/bpig.49 (*in Polish*).
- Uliasz-Misiak, B. 2016. Water accompanying hydrocarbon deposits as a potential source of iodine, lithium and strontium (*Wody towarzyszące złożom węglowodorów jako potencjalne źródło jodu, litu i strontu*). *Gospodarka Surowcami Mineralnymi – Mineral Resources Management* 32(2), pp. 31–44, DOI: 10.1515/gospo-2016-0012 (*in Polish*).

USGS 2021 – *Interior Releases 2018's Final List of 35 Minerals Deemed Critical to U.S. National Security and the Economy*. [Online] <https://www.usgs.gov/news/interior-releases-2018-s-final-list-35-minerals-deemed-critical-us-national-security-and> [Accessed: 2021-11-12].

WMP 2021 – *World Mineral Production 2015–2019*. British Geological Survey, 2021. Keyworth, Nottingham.

Worldbank 2021. [Online] <https://wits.worldbank.org/trade/comtrade/en/country/ALL/year/2018/tradeflow/> [Accessed: 2021-11-12].

## LITHIUM SOURCES AND THEIR CURRENT USE

### Keywords

lithium deposits, production, market, trade, prices, recycling, substitution

### Abstract

The lithium market has experienced an unprecedented boom in recent years like a “golden age” and is one of the fastest growing raw material markets in the world. The fast growing demand for lithium is mainly related to the increase in the production of lithium-ion batteries used in electric or hybrid vehicles and portable electronic equipment, and to a lesser extent, in other strategic fields (military, nuclear technologies). This was reflected in a significant change in the structure of consumption, an increase in international trade and in the price of lithium raw materials. Moreover, in 2018 lithium was listed as a critical element for the national security and economy of the United States, and in 2020 it was also listed as a critical raw material for the European Union economy. It is also a time of increased exploration for new deposits, as well as mining processing and recycling. As a result, global lithium reserves have doubled in the last six years. All this prompted the authors to prepare an article in which the sources of lithium minerals and their resources, the basic factors determining the economic situation on the market, their prices and the possibilities of recycling and substitution are presented and assessed. Attention is also paid to the role of companies operating in Poland as significant partners on the European market of lithium-ion batteries. Lithium oxide and hydroxide and lithium carbonate are the main lithium raw materials used in Poland. In the absence of the country having its own deposits, they are imported, and the main suppliers are Chile, Western European countries and Russia.

## ŹRÓDŁA LITU I ICH AKTUALNE WYKORZYSTANIE

### Słowa kluczowe

złoża litu, produkcja, rynek, handel, ceny, recykling, substytucja

### Streszczenie

Rynek litu przeżywa w ostatnich latach bezprecedensowy boom nierzadym „złoty wiek” i jest jednym z najdynamiczniej rozwijających się rynków surowcowych na świecie. Szybko rosnące zapo-

trzebowanie na niego związane jest przede wszystkim ze wzrostem produkcji baterii litowo-jonowych wykorzystywanych w pojazdach elektrycznych lub hybrydowych oraz w przenośnym sprzęcie elektronicznym, a w mniejszym stopniu także w innych strategicznych dziedzinach (wojskowość, technologie nuklearne). Znalazło to odzwierciedlenie w znaczącej zmianie struktury konsumpcji, wzroście handlu międzynarodowego i cen surowców litowych. Ponadto, w 2018 r. lit znalazł się na liście pierwiastków krytycznych dla bezpieczeństwa i gospodarki Stanów Zjednoczonych, a w 2020 r. jako surowiec krytyczny dla gospodarki Unii Europejskiej. Jest to również czas wzrostu poszukiwań nowych złóż, jak również przetwarzania górniczego i recyklingu. W efekcie światowe zasoby litu podwoiły się w ciągu ostatnich sześciu lat. Wszystko to skłoniło autorów do przygotowania artykułu, w którym przedstawiono i oceniono źródła minerałów litu i ich zasoby, podstawowe czynniki determinujące koniunkturę na rynku, ceny, a także możliwości recyklingu i substytucji. Zwrócono również uwagę na rolę firm działających na terenie Polski jako znaczących partnerów na europejskim rynku baterii litowo-jonowych. Tlenek, wodorotlenek oraz węglan litu to główne surowce stosowane w Polsce. Z powodu braku krajowych złóż są one importowane, a głównymi dostawcami są Chile, kraje Europy Zachodniej oraz Rosja.

